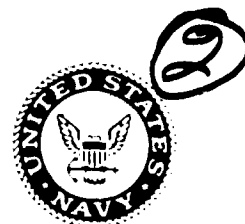


# Naval Research Laboratory

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## **Plasma Reflectors for Electronic Beam Steering in Radar Systems**

WALLACE M. MANHEIMER

*Senior Scientist Fundamental Plasma Processes  
Plasma physics Division*

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## CONTENTS

I. INTRODUCTION .....	1
II. PREIONIZATION .....	3
III. THE MAIN IONIZATION .....	7
IV. THE DECAY OF THE IONIZATION .....	11
V. DISCUSSION AND CONCLUSIONS .....	14
APPENDIX .....	15
ACKNOWLEDGMENT .....	17
REFERENCES .....	18

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# PLASMA REFLECTORS FOR ELECTRONIC BEAM STEERING IN RADAR SYSTEMS

## I. Introduction

A phased array radar has a tremendous response time over other types of radars. The beam can be electronically steered by rapidly adjusting the phases of the individual radiating elements. The response time can be so rapid that an initial transmitted beam can be sent in one direction and other transmitted beams can be sent in completely different directions; the antenna can then be reset to receive the original and all subsequent transmitted beams. Alternatively, the antenna can be set to send and receive a beam in one direction and then send and receive a beam in another direction. The phased array radar is the basis of both Aegis and Pave Paws. One difficulty with the phased array, however, is that it is generally restricted to low frequency. The radiating elements have to be less than half a wavelength apart to avoid grating lobes. Thus at high frequency, the packing density is high. Also for a given antenna size, the number of elements gets large. In practice, phased arrays with meter-sized or greater dishes are not generally used for frequencies greater than about 3 GHz.

In this study we examine the use a plasma mirror as an element that can electronically steer a beam at much higher frequency.<sup>1</sup> Although the frequency and antenna size are nearly arbitrary, we consider two cases: a 2 meter antenna at X-band for ship-based use, and a 10-m 60 GHz antenna for space-based use. The latter case has been considered by the Strategic Defense Initiative. This phased array would have more than  $10^7$  elements, which is about  $10^4$  times as many as are conventionally used in phased arrays. Our result is that an electronically steered plasma reflector could be a practical possibility.

The problem of forming a plasma reflector is first localizing the discharge. There are many possible ways to do this, but the most viable at this time seems to be photo ionization of aromatic impurities with an excimer laser. The light would be directed with a rotating mirror. This is examined in Section II. The presence of the seed ionization localizes the discharge. The main ionization is then produced with a microwave discharge. We find that the energies and powers required for the microwave system are within the state of the art for the X-Band case and are extensions of the state of the art for the 60 GHz case. This is considered in Section III. Another problem when using this plasma reflector is eliminating

the electrons in the reflection chamber before the second ionizing pulse is sent in. To do this, a small amount of an electronegative impurity (such as  $\text{SF}_6$ ) must be added. This is examined in Section IV. In Section V, results and potential small-scale experiments to test various aspects of the concept are discussed. Finally the Appendix discusses other preionization schemes which appear to be difficult with the present state of technology. However further technical advances could render them very attractive and allow for full electronic beam steering with no mechanical components.

## II. Preionization

In this section we consider the localization of the initial seed ionization. For a radar application, the plane of the mirror must be changed very quickly, around one or two axes, on a time scale from milliseconds down to tens of microseconds. In this initial design study, we consider separate schemes that allow for rotation of the mirror on one or two axes.

We describe first a scheme for an agile mirror that rotates about a single axis and then for the case of rotation about two axes. Laser ionization of trace amounts of aromatics with an excimer laser is used for preionization and localization of the breakdown. The laser beam, perhaps initially a centimeter in cross section, is defocused with a diverging cylindrical lens. After a certain propagation distance, the beam cross section is the required size, approximately 2 meters by 1 centimeter. (Cross sectional widths smaller than 1 cm are possible also if laser energy must be reduced. However cross sections much less than a millimeter will lead to significant diffractive spreading of the beam over the 2m propagation distance.) At this point it is refocused to a parallel beam by a converging cylindrical lens. This beam then impinges on a rotating polyhedral mirror, which for the sake of defining the system, we consider to be an octagon. The orientation of the mirror at the instant of the laser light reflection defines the plane of seed ionization in the mirror. This is determined by the time at which the laser is fired with respect to the orientation of the octagon. By using an octagon, the plane of the seed ionization can be varied by  $45^\circ$ , so the angle of the final radar beam can be varied by  $90^\circ$ . The face of the octagon is assumed to be about 2 centimeters, corresponding to a diameter of about 5 cm. In conventional rotating mirror shutters, rotations speeds of 3000 revolutions per second have routinely been achieved (as of 1967) and speeds of 18,000 revolutions per second have been achieved in specially designed mirror systems.<sup>2</sup> For X-band antennae, we consider the speed of 3000 revolutions per second. Thus the time for one eighth of a revolution is about 40  $\mu$ s. This represents the longest wait for determining the plane of a new mirror as long as the remnants of the previous mirror have cleared away. For the space-based case where

faster agility might be required, we consider the higher speed, implying a waiting time of 7  $\mu$ s.

The ionization of aromatic molecules with an excimer laser has been discussed, and experiments on it have been done at both NRL<sup>3</sup> and the Sandia National Laboratory.<sup>4</sup> The ionization is generally regarded to be a two-photon process; the number density of electrons generated is given by

$$n_e(\text{cm}^{-3}) = n_0(\text{cm}^{-3})\alpha(\text{cm}^4/\text{W})I^2(\text{W}/\text{cm}^2)\Delta t(\text{s})/h\nu \quad (1)$$

where  $n_0$  is the molecular density of the aromatic,  $\alpha$  is the two photon ionization coefficient,  $I$  is the laser irradiance,  $\Delta t$  is the half width of the laser pulse, and  $h\nu$  is the photon energy. In the Sandia work, the largest  $\alpha$  value found was about  $10^{-25}$  for *n,n*-Diethyl aniline. To estimate the seed ionization produced, we consider a 1-Joule laser pulse with a 20-ns half width at a wavelength of 248 nm (a krypton fluoride laser). This is a commercially available laser at a replate of 100 Hz according to the *1990 Laser Focus Buyers Guide*. If the beam cross section of this laser is 1 cm by 200 cm, the electron density is

$$n_e = 2 \times 10^{-4} n_0 \quad (2)$$

Clearly with the choice of initial aromatic density  $n_0$ , there also is a choice of the initial electron density  $n_e$ . Of course  $n_e$  must be small enough that the ionization is not a drain on the laser energy; that is the ionization must be uniform along the laser path length. The actual choice of  $n_0$  will undoubtedly depend on the required parameters of the radar system. Here we consider  $n_e$ 's relatively small so that if the electrons are produced along discrete lines, these lines diffuse together rapidly by free diffusion, rather than by the much slower ambipolar diffusion. This will be discussed further in the next section. We consider here an example of a seed molecular density of  $5 \times 10^9 \text{ cm}^{-3}$  of the aromatic, which will give an initial electron density of  $10^6$ . This should be enough of a seed electron density for build up with an rf discharge.

For the case of a reflector plane which is agile in two dimensions, a variant of the system is the following. Instead of a single excimer laser, we use a large number of much smaller lasers. For instance a 50- $\mu$ J laser focused to a spot 1 mm in each direction

has the same irradiance as the larger laser we have considered. Again, according to the *1990 Laser Focus Buyers Guide*, such a laser is compact and inexpensive. If 400 of them are used for the X-band case, for which we have considered a 2-m antenna, this implies 400 discharge channels (about 6 per radar wavelength), which can be individually controlled to localize the reflector.

We imagine again the rotating mirror. Now many individual laser beams are reflected from it. The time at which, for instance, the center beam is fired defines the initial axis of the plasma reflector. However the other lasers do not have to be fired simultaneously. By programming the time sequence at which the other lasers fire, the orientation of the seed ionization can be selected perpendicular to the initial axis defined by the laser beam at the center.

This scheme gives reflector shape that has no curvature in the direction of the laser beam but does have some curvature in the direction perpendicular to the laser beam. To investigate this, let the rotating mirror be along the z axis of a co-ordinate system. Let the slope of the laser beam in the x-y plane vary in z according to  $1+\beta z$ , where for the sake of being specific, we assume a slope of unity at the center of the mirror, which is assumed to be  $z=0$ . The quantity  $\beta$  is determined by the timing of the firing of the laser beams. The equation of the surface formed by the laser beams is

$$y = (1+\beta z)x .$$

If we assume that  $\beta D$  is small (where  $D$  is the size of the reflector), the plane of the mirror at  $z=0$  is tilted by an angle  $\beta D/2$ . Perpendicular to the laser beam, the mirror radius of curvature is roughly  $\beta^{-1}$ . When the radar wave reflects from this mirror, there can be some additional focusing or defocusing, depending upon which side the radiation is incident from. The utility or nonutility of such an antenna will depend on the requirements of the radar system. As we discuss in the appendix, there are other potential schemes to form reflectors that can be better shaped, but which require technology that is not as available at the present time. Finally, in any scheme that generates a reflector by using a sequence of line discharges rather than a planar discharge, one must be concerned with how these lines diffuse together to form a plane. This is discussed in the next section. At minimum, the spacing of



the lines must be close enough that more than two lines per radar wavelength occur at their widest separation, making it impossible to form coherent grating lobes. Thus with this scheme, a trace amount of aromatic preionized by an excimer laser reflected from a rotating mirror can produce a reflector that can be electronically steered about one or two axes. Around one of these axes however, the reflector has some curvature that is dependent on the tilt angle about this axis.

### III. The Main Ionization

We now consider producing the main plasma. The initial electron number density is about  $10^6 \text{ cm}^{-3}$ . This is produced by the laser ionization from an aromatic impurity having a molecular number density of about  $10^{10} \text{ cm}^{-3}$ . The main plasma we consider is argon, and the argon number density is much larger than that of the aromatic. The elastic collision scattering cross section for electrons in argon is shown in Fig 1, and the ionization cross section for argon is shown in Fig 2. The ionization threshold energy is about 15 eV for argon. The electron mean free path before elastic scattering or ionization is given by  $(n_a \sigma)^{-1}$ , where  $n_a$  is the number density of argon atoms and the  $\sigma$  is the cross section for the particular process. The rate for the process is given by  $\nu = n_a \sigma v$ , where  $v$  is the electron velocity.

Once we produce the ionized layer, we want it to reflect the radar wave without very much loss. Thus the collision frequency in the plasma must be much less than the radar frequency. Because a microwave breakdown generally produces a maximum electron density equal to the critical density at the breakdown frequency, we consider the case of the breakdown frequency equal to twice the radar frequency. Thus the maximum ion density produced will be four times the critical density at the radar frequency. The power to produce the rf discharge is generally a minimum when the electron elastic collision frequency is equal to the rf frequency (the Paschen minimum). However this would render the collision frequency twice as high as the radar frequency, implying large loss upon reflection of the radar wave. For simplicity, we consider the collision frequency to be about one tenth of the radar frequency, although we recognize that an optimization of the radar-plus-ionizer system might arrive at a somewhat different argon density. The actual collision frequency depends on the temperature. Although ions are not produced from collisions with electrons having energy below 15 eV (as apparent from Fig 1.), the actual plasma temperature upon reflection may be lower because the plasma may have cooled or have been maintained at a different temperature by the microwaves. The cooling rate is given roughly by twice the collision rate times the ratio of the electron to the argon mass. We consider a radar frequency of  $\omega = 2\pi f = 5 \times 10^{10}$  and an ionizer at a frequency of  $10^{11}$ .

If the plasma temperature upon reflection is taken to be 1 eV, the argon density becomes  $6 \times 10^{17} \text{ cm}^{-3}$  for the collision frequency to be one tenth of the radar frequency for the X-band case and  $4 \times 10^{18}$  for the 60 GHz case.

The ionization is assumed to be produced by an avalanche discharge. When an electron is accelerated to an energy of slightly over 15 eV, the ionization cross section is  $10^{-17} \text{ cm}^2$ . Then the time to produce an electron by collisional ionization is less than a nanosecond. Thus the time to produce the discharge is determined almost entirely by the time to heat energize the electrons to the ionization threshold. The heating rate of electrons in the rf fields is given by<sup>5,6</sup>

$$dE/dt(\text{eV/s}) = 6 \times 10^{17} I(\text{W/cm}^2) \nu_c / (\nu_c^2 + \omega^2), \quad (3)$$

where  $\nu_c$  is the elastic collision frequency and  $\omega$  is the frequency of the ionizer. Note that  $\nu_c$  is a function of energy but is much less than  $\omega$ . From Fig. 1, the increase of  $\sigma_c$  with energy is roughly linear at small energy, so the elastic collision frequency increases roughly as  $E^{3/2}$ . For an argon density of  $6 \times 10^{17}$ , collision frequency is roughly equal to

$$\nu_c(E) = 5 \times 10^9 E^{3/2}$$

(4)

for  $E < 15 \text{ eV}$ .

Then we can integrate Eq. (3) in time to calculate the time to heat the electrons from 1 to 15 eV for the X-Band case. This time is about  $100 \mu\text{s}$  for a microwave irradiance of  $0.1 \text{ W/cm}^2$ . The time is about 100 ns for an irradiance of  $100 \text{ W/cm}^2$ . This is the e folding time for electron density; if about 10 e folds are needed, the pulse times are about 1 ms and  $1 \mu\text{s}$  respectively. For a 2-m sized reflector, the total powers become 4 kW and 4 MW respectively. In either case the pulse energy is 4 Joules, or about 300 eV per electron ion pair for a 1-cm-thick reflector. Also it is assumed that the plasma is produced faster than decay processes reduce the electron density. As we will see in the next section, this is only qualitatively true, since the decay processes must also be rapid to efficiently sweep away the plasma between radar pulses. Finally, the radar pulse cannot significantly affect the plasma reflector.

Typically in radar systems, a power of a megawatt for a microsecond or so is a reasonable upperbound for the pulse energy. Thus the radar pulse energy is less than the ionizer energy. Furthermore, since the radar pulse is at lower frequency, it does not penetrate the reflector well either. Hence the constraint that the radar pulse does not affect the reflector does not look like a serious one for potential radar systems. Further study could undoubtedly optimize the neutral density to minimize the power of the entire system, radar plus ionizer, once the parameters of the radar are specified.

For the former, slow case, we envision a mirror that remains in position for several milliseconds, a mirror that serves as the antenna for both the transmitted and reflected radar wave. For the latter, fast case, we envision examining several distant targets. A mirror serves as an antenna for the transmitted pulse and then different mirrors are set up for different transmitted pulses several tens of microseconds later. At a later time then (perhaps 100  $\mu$ s to 1 ms), the mirrors are reconstructed for the received signals. The microwave power, energy, and pulse time are all within the state of the art of, for instance, magnetrons at frequencies of 15 to 20 GHz. These existing magnetrons are also typically very efficient; they can be designed to optimize efficiency at 50% or more. Furthermore, once the ionization is produced, it might be desirable to maintain the microwave ionizer power at a much lower power to maintain the electron temperature at some desired value, for instance at a temperature of 1 eV.

For the 60 GHz case, the irradiances are 6 times greater to achieve the same effect in the same time. Thus to generate the reflector in 1  $\mu$ s, an irradiance of about 600 W/cm<sup>2</sup> is required, and with an ionizer frequency of 120 GHz. The total power to produce the ionization over the 10-m aperture is 600 MW. A 1 MW, 140 GHz gyrotron has been developed at MIT,<sup>7</sup> and a multimegawatt gyrotron at 94 GHz is being designed and built at NRL.<sup>8</sup> Although the peak power is high, the average power might or might not be, depending on the repetition rate. However a 10-million-element phased array is difficult also, and the plasma reflector could well be competitive.

The plasma should be very well localized at the position of the seed ionization under certain very broad conditions. Thus the density gradient should be very steep compared to the radar

wavelength, and the reflection should be as off a sharp surface. The conditions for the main breakdown to remain localized are that the plasma remain transparent to the ionizing microwave radiation at the higher frequency and that the breakdown time be small compared to the ambipolar diffusion time. The breakdown will be transparent to the ionizer as long as the plasma density is less than the critical density at the ionizer frequency. As soon as the critical density is reached, the reflected or transmitted signal of the ionizer will change abruptly, and this is the signal to turn it off. Since the electron density is high, the ambipolar diffusion coefficient is given by  $T_e/Mv_c$ , where  $T_e$  is the electron temperature and  $M$  is the ion mass. Because the ion mass is so large and the thickness of the plasma is of centimeter scale, the ambipolar diffusion time is very long. Therefore the plasma should remain planar, with a sharp density profile as far as reflecting the radar wave is concerned. The quality of the reflection will be very high unless some anomalous process occurs that wrinkles the sheet.

We conclude with a discussion of the blending of the individual line breakdowns to form a smooth sheet. The diffusion coefficient is given by  $T_e/mv_c$  where  $m$  is the electron mass. Since the electron density is very low in the preionized plasma, the Debye length is long, so that the diffusion is governed by free electron diffusion rather than by ambipolar diffusion. Note also that free diffusion is a much faster process than ambipolar diffusion. For instance if the seed electron density is  $10^6 \text{ cm}^{-3}$ , and the electron temperature is 3eV (which can be controlled by the breakdown rf at low power), the Debye length is about 2 cm, while the line breakdowns are perhaps half a centimeter apart. Then the time for the breakdowns to diffuse together is about a microsecond. When the line breakdowns are determined by reflections of individual laser beams from a rotating mirror, the individual lines diverge from one another. However if  $\beta D$  is small and the total length of the reflector is of order  $D$ , the final spacing of the lines is about the initial spacing.

#### IV. The Decay of the Ionization

The agile reflector for a radar system must be concerned not only with producing the mirror to reflect a single radar pulse, but also with sweeping it away between pulses so that the next mirror can be set up for the next pulse. Recombination is governed by

$$dn_e/dt = -p n_e^2 \quad (5)$$

The largest two body recombination coefficient for argon is the dissociative recombination coefficient,<sup>1</sup> is given roughly by  $p=10^{-6}$  cm<sup>3</sup>/s. Thus, assuming all argon ions are diatomic, the time for the electron density to decay below 10<sup>6</sup> cm<sup>-3</sup> (the laser preionization density) is more than a second. Diffusion increases the time even further by spreading out the plasma and reducing the electron density while keeping the total electron number constant. Hence recombination is not a fast enough process to sweep away the residual electrons. Thus an electro-negative element must be added to soak them up in time for the next pulse. The most electro-negative gas that is reasonably safe to handle is probably SF<sub>6</sub><sup>9</sup> whose maximum attachment cross section is about 2x10<sup>-16</sup> cm<sup>2</sup>. This attachment coefficient maximizes at an electron temperature of about 0.1 eV. While the reflector is being used, the ionizer rf source may still be used as a heater (to maintain an electron temperature much larger than 0.1 eV) to prevent attachment. Thus the heater microwave source at higher frequency can play a role of not only creating the ionization but also of controlling it to optimize total performance. If the number density of SF<sub>6</sub> is denoted  $n_s$  and if the electron temperature is about 0.1 eV, then the time constant for the decay of electron density due to attachment is given roughly by

$$\tau = 10^9/n_s \quad (6)$$

A number density of SF<sub>6</sub> of 10<sup>12</sup> cm<sup>-3</sup> gives a decay time of 1 ms, and a density of 10<sup>15</sup> gives a decay time of 1  $\mu$ s. In the former case the mirror would be maintained for several milliseconds and would serve as an antenna for both the incident and reflected radar wave for a target. In the latter case, the mirror would exist for several microseconds so several radar pulses would be sent out in different directions before the mirror is reconstructed to receive one of the reflected pulses. Intermediate decay times could also be selected

by varying the SF<sub>6</sub> density; the choice would depend on the application.

At higher electron density, above  $10^{12} \text{ cm}^{-3}$ , three-body recombination is also a potential loss mechanism<sup>10</sup>. Thus, it could play a role in limiting the lifetime of the reflector for the 60 GHz case. However, three-body recombination is most potent at very low temperatures, well under 1 eV. At higher temperatures, electrons are collisionally reionized before they can decay back to the ground state. The temperature dependence quoted in Ref. 10 has the three-body coefficient decreasing as  $T_e^{-4.5}$ , so if the plasma is maintained by the heater at a temperature of an eV or so, three-body recombination should not be an important limitation on the reflector characteristics. However when the radar and heater are turned off, the plasma will cool and at high electron density, three body recombination will speed the electron losses at high electron density.

Regarding the longer term effects, the electrons attached to the SF<sub>6</sub> would charge exchange with the positive argon ions according to Eq.(5) with some coefficient  $p$  that is probably quite small due to the slow thermal velocity of the positive and negative ions. The decay would take a very long time; after many pulses the chamber would have a large number of positive and negative ions. This could have some long term effect on the system, which would have to be investigated. Most likely, a closed system could not be used, but rather there would be an input where the proper portions of aromatic, argon, and SF<sub>6</sub> would be pumped in, and an output where the gases would be pumped out. The gases would have to be pumped in and out, not only to limit the positive and negative ions before their density becomes too high, but also to ensure that the chemical compositions remain as desired, in all likelihood the aromatic particularly would degrade chemically in the plasma environment after some length of time. It is not clear just what the pumping speed must be to maintain the system over long time. However it is reassuring that the fractional ionization is quite low, as is the fractional ionization of the aromatic by the laser. It is only the SF<sub>6</sub>, which at the lowest density quoted, that for millisecond decay, has a density comparable to the electron density. In this case, a higher density of a less electro-negative gas would be preferable.

Another important issue is the pressure loading on the chamber. For the 10 GHz case, the pressure over a 2m system is

about an atmosphere over the entire surface. The chamber could be something like a glass sphere whose thickness is an integral number of half radar wavelengths. Alternatively one could envision a spherical birdcage, whose ribs provide the structural support and are made of a nonconducting material. A transparent film like mylar could then provide the vacuum. Since the film is much less than a radar wavelength, it would be transmissive at any radar wavelength. Outgassing of the vacuum wall is also a consideration. However since working gasses are to be recycled, and the pressure inside is not particularly low, the outgassing is expected to be a transient effect when the system is first used, rather than a permanent difficulty.

Figure 3 is a schematic of the entire agile mirror system which we have discussed in these three sections.



## V. Discussion and Conclusions

We have discussed a possible system for electronically steering radars. We concentrated on the two cases of ship-based X-Band radars and space-based 60 GHz radars. The concept is based on producing an electron layer at the critical density for the radar frequency. The layer is produced by a combination of laser and microwave breakdown. Our preliminary study shows that the reflector can be quickly rotated on one or two axes with a simple and relatively standard optical system. Also it shows that the reflector can be both produced and localized at reasonable power. For long-term viability, it almost certainly cannot be based on a closed system. Gas must flow in and out at some rate, which was not calculated here.

Several issues regarding the agile mirror can probably be answered with laboratory experiments. With a small laser having energy of tens of millijoules, cylindrical or narrow planar seed plasmas can be produced for build up with a microwave system. These plasmas could serve as a testbed for plasma buildup by investigating the parameters of the microwave system required for optimum plasma buildup. Also they could be used to investigate the long- and short-term plasma decay. For instance the pumping rate and gas composition for long-term viability could be obtained in this way. Furthermore, scattering experiments could be done in either a cylindrical or a planar configuration to test the basic mechanisms of radar reflections from such plasmas. If further experimental and theoretical work indicates the viability of the agile plasma mirror, it could enhance the capability of some military and civilian radar systems.

## Appendix

### Potential Fully Electronic Ways to Initiate a Discharge Agile About Two Axes

We briefly consider other ways of producing the seed ionization that would not use a rotating mirror. These are electron beam ionization and laser diode ionization. Our conclusions are that these systems are not now viable for meter sized antennae. However future potential technical improvements could render them very attractive.

#### A Electron Beam Preionization

Here we consider the use of an energetic electron beam to produce the seed ionization. The beam is fired from a cathode, and the anode is across the chamber. Since the anode is a conductor, a portion of the chamber must be opaque to the ionizing and radar microwaves. However this should not be a serious impediment because the geometric area covered by the conductor should be relatively small if the plane is to pivot (say  $45^\circ$ ) about two axes, and the use of a grid of parallel wires could serve as a dc anode, but could still transmit microwaves with the proper polarization. The main potential advantages of electron beam ionization are first that with electrostatic deflection, the beam can be deflected in two transverse directions so that the mirror can be rotated about two axes rather than one, rather like forming a picture on a TV picture tube. Second, the beam can be fired at any time without waiting for a mirror to be in the correct position.

For high electron energy, both the elastic and ionization cross section for argon are about equal and decrease as  $E^{-1}$ . An approximate expression is

$$\sigma_c(\text{cm}^2) = \sigma_a = 10^{-16}/E(\text{keV}) \quad (\text{A1})$$

A fundamental requirement is that the electron beam crosses the chamber without being scattered, which we take to mean that the chamber dimension  $D$  is half the mean free path at the beam energy. For the antenna size  $D$ , we find that the beam energy, antenna size, and argon density are constrained by

$$E(\text{keV})/n_a(\text{cm}^{-3})D(\text{m}) > 2 \times 10^{-14} \quad (\text{A2})$$

For now however, if we assume a voltage of 100 keV as a reasonable maximum, the argon density must be less than  $2.5 \times 10^{15}$ . However with such a low density, Eq. (3) shows that the microwave irradiance  $I$  is about a factor of 250 larger to do the same thing as described in Section 3. The energy penalty is even greater for the 60 GHz 10 m antenna if the ionization voltage maximum is assumed to be 100 keV.

Thus a substantial energy and power penalty occurs unless very high energy electron beams become practical. If we assume that higher energy can be produced with an inexpensive and compact accelerator, perhaps an rf accelerator, this method of preionization becomes very attractive. It could also be attractive if much smaller antenna sizes would be of interest.

#### B. Preionization with Compact Laser Diodes

Another possibility is the use of laser diodes. These laser diodes are very compact and inexpensive. The idea would be to place a large array of them around the ionization region and then define the reflector plane by the subset of the array that is fired. The problem with this scheme is that so far these laser diodes operate at a minimum wavelength of about  $1\mu\text{m}$ . Furthermore the beam quality is not high enough for the efficient operation of frequency doublers and quadruplers. If these laser diodes could be developed to the point where they operate at, or could be frequency multiplied to a wavelength to, about  $0.25\mu\text{m}$  and were compact and inexpensive, they would be a very attractive way of electronically selecting the plane of reflection without mechanical components.

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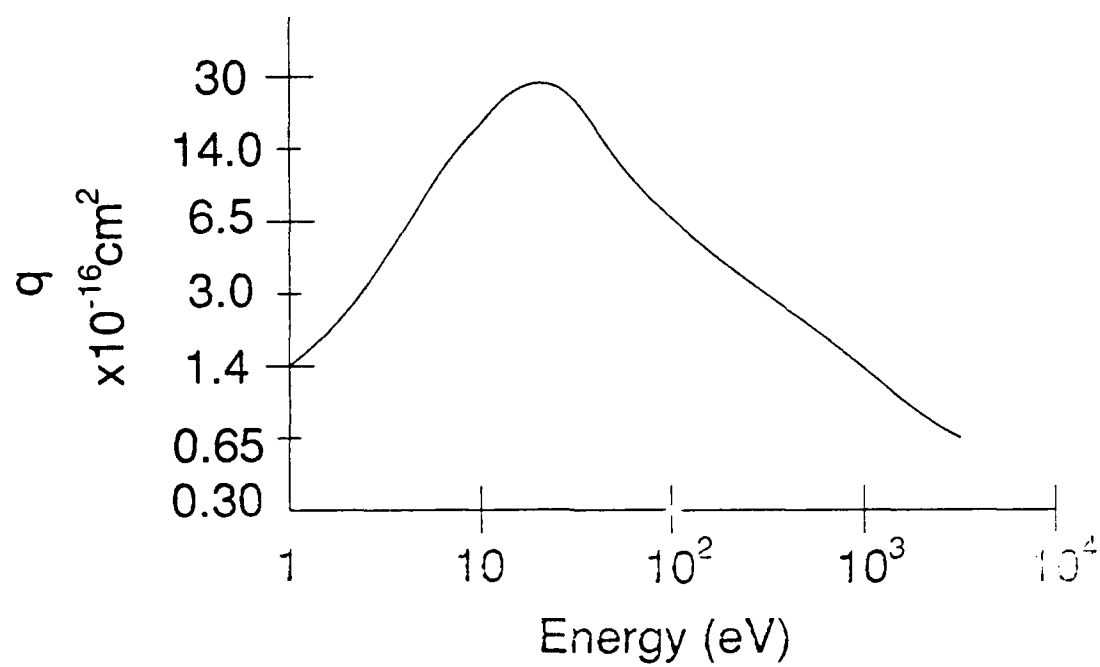


Fig. 1 — Elastic cross section for electron scattering by argon as a function of energy

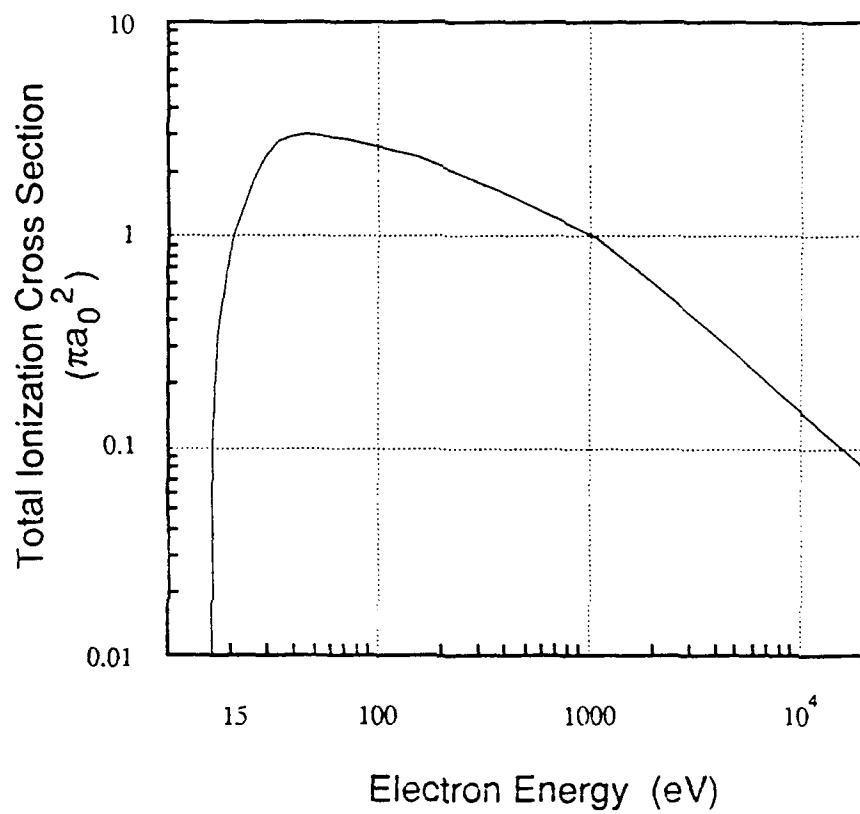


Fig. 2 — Ionization cross section of argon by electron impact as a function of energy

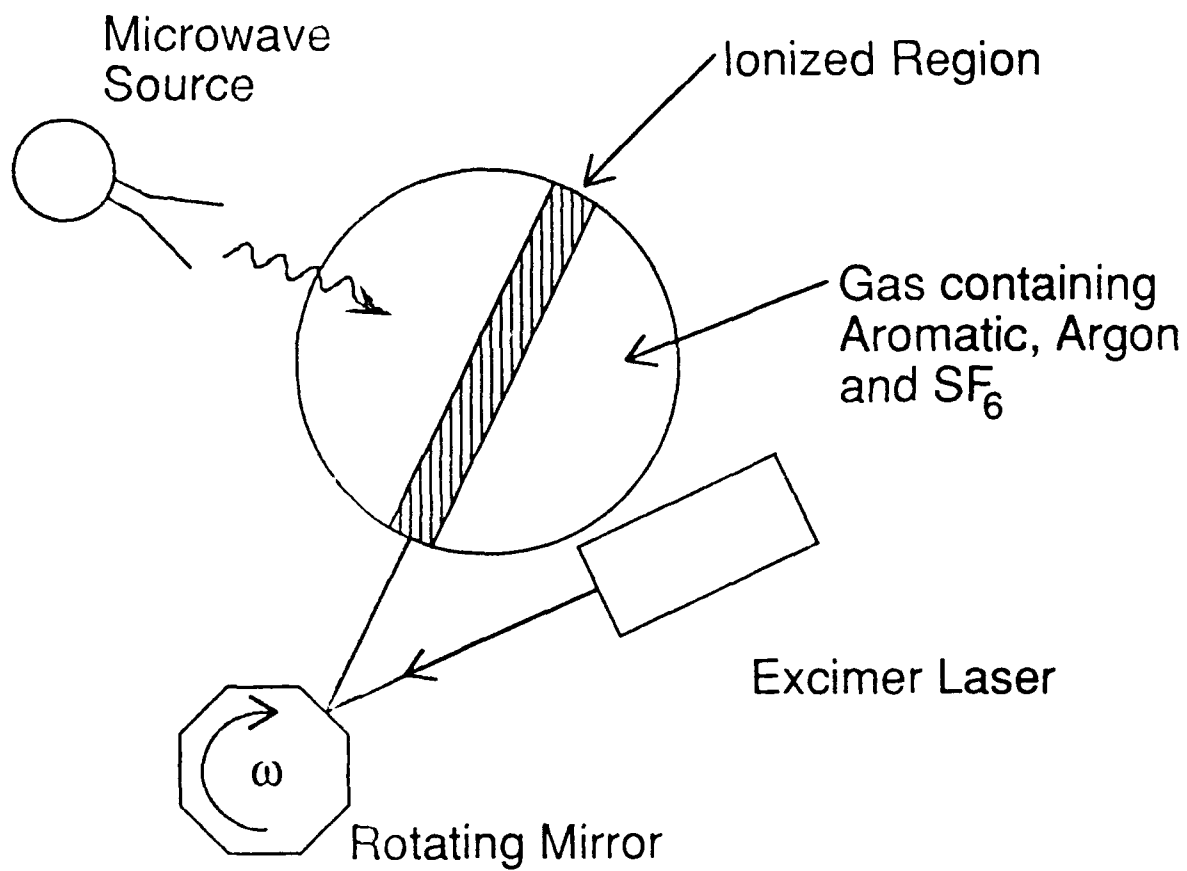


Fig. 3 — The agile mirror system